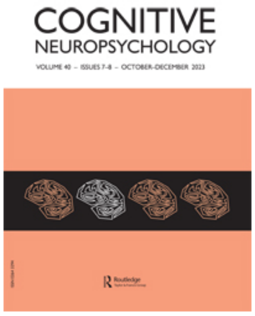

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Characterizing different types of developmental dyslexias in French: The Malabi screener

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ABSTRACT

Reading is a complex process involving multiple stages. An impairment in any of these stages may cause distinct types of reading deficits– distinct types of dyslexia. We describe the Malabi, a screener to identify deficits in various orthographic, lexical, and sublexical components of the reading process in French. The Malabi utilizes stimuli that are sensitive to different forms of dyslexia, including "attentional dyslexia", as it is traditionally refered to, characterized by letter-to-word binding impairments leading to letter migrations between words (e.g., "bar cat" misread as "bat car"), and "letter-position dyslexia", resulting in letter transpositions within words (e.g., "destiny" misread as "density"). After collecting reading error norms from 138 French middle-school students, we analyzed error types of 16 students with developmental dyslexia. We identified three selective cases of attentional dyslexia and one case of letter-position dyslexia. Further tests confirmed our diagnosis and demonstrate, for the first time, how these dyslexias are manifested in French. These results underscore the significance of recognizing and discussing the existence of multiple dyslexias, both in research contexts when selecting participants for dyslexia studies, and in practical settings where educators and practitioners work with students to develop personalized support. The test and supporting materials are available on Open Science Framework (https://osf.io/3pgzb/).

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1. Introduction

Reading is a complex activity involving many processes and pathways linking visual, language, and conceptual systems of the brain, as demonstrated by brain-imaging studies comparing illiterates and literates (Dehaene et al., 2010, 2015a; Price, 2012) and identifying multiple changes in the brain over the course of learning to read (Brem et al., 2010; Dehaene-Lambertz et al., 2018; Monzalvo & Dehaene-Lambertz, 2013; Wandell & Yeatman, 2013). This multi-module complexity is clearly illustrated by the variety of case studies of acquired dyslexia following brain damage in adults (Caramazza et al., 1985; Coltheart, 1981; Coltheart & Funnell, 1987; Coslett, 2000; Coslett & Turkeltaub, 2016; Ellis, 1984; Friedmann et al., 2012; Friedmann & Gvion, 2001; Lambon & Ellis, 1997; Lambon Ralph & Patterson, 2005; Marshall & Newcombe, 1973; Newcombe & Marshall, 1981; Patterson, 1981; Patterson & Lambon Ralph, 1999; Shallice & Warrington, 1977) and the diversity of reading difficulties presented in cases of developmental dyslexia (Castles & Coltheart, 1993; Coltheart & Kohnen, 2012; Ellis & Young, 2015; Friedmann & Coltheart, 2018; Friedmann & Haddad-Hanna, 2014a; Jackson & Coltheart, 2001; Marshall, 1984a, 1984b; Temple & Marshall, 1983). However, current screening and remediation tools are rarely optimized to cover the possibility of multiple different deficits.

Much of the research has been focused on trying to explain dyslexia as a single underlying cognitive deficit, without converging on what this deficit might be. For example, from the perspective of the visual system, multiple theories of dyslexia have surfaced, spanning from retinal anomalies (Le Floch & Ropars, 2017) to a dysfunctional magnocellular pathway (e.g., Stein & Walsh, 1997) or deficient visuo-spatial attention (e.g., Bosse et al., 2007; Valdois et al., 2004; Vidyasagar & Pammer, 2010). The dominant hypothesis, however, is

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that dyslexia relates to an underlying phonological deficit (Landerl et al., 1997; Ramus, 2003; Vellutino et al., 2004), characterized by difficulties in perceiving and manipulating phonemes, the smallest sound units of spoken words that distinguish one word from another (Goswami & Bryant, 1990).

The fragility of core deficit hypotheses is that the diagnosis of dyslexia is filtered through the unitary theory itself, and in many cases, the person's difficulties in reading are not thoroughly analyzed. For example, researchers and clinicians assessing for phonology-related core deficits typically make a diagnosis of dyslexia using oral phoneme awareness tasks such as phoneme deletion, phoneme fusion, and pseudoword repetition (Elbro & Jensen, 2005; Landerl et al., 1997; Peterson & Pennington, 2012; Ramus et al., 2003; Saksida et al., 2016; Wagner & Torgesen, 1987). The argument is that a deficit in the person's phoneme awareness, exemplified in language difficulties pre-existing reading, causes dyslexia. We agree that poor phoneme processing can result in reading difficulties, but we also argue that this methodology is at risk of filtering for certain types of dyslexia while excluding others, generating both false positives and negatives (Scarborough, 1998; Torgesen, 2002). In the particular case of using phoneme awareness tasks to identify dyslexia, false positives could stem from lack of appropriate reading experience, as literacy is known to facilitate phoneme processing (Dehaene et al., 2015a; Morais et al., 1979); and false negatives could arise from failing to carefully test reading itself in the absence of a phonological deficit. Indeed, various studies have reported individuals with dyslexia who showed no difficulties on pseudoword repetition tasks, phonological span tasks, or phonological awareness tasks (Castles, 1996; Castles & Friedmann, 2014; Friedmann & Rahamim, 2007; Güven & Friedmann, 2019, 2021, 2022; Khentov-Kraus & Friedmann, 2018a).

1.1. The multiple deficit theory of dyslexia, and its screening

Several authors, even those who favor the phonological hypothesis, have recognized that multiple deficits may exist in developmental dyslexia (e.g., Ramus et al., 2003; Siok et al., 2009). Thus, another methodology has been to develop tests that seek to understand dyslexias (in the plural) as arising from multiple possible deficits, depending on the locus of impairment within the complex architecture for reading (Castles et al., 2009; Castles & Coltheart, 1993; Ellis et al., 1996; Temple & Marshall, 1983). This line of research draws upon models of multiple reading pathways in expert readers such as the Dual-Route model (Coltheart, 2005; Friedmann & Coltheart, 2018) and its computational variants (Coltheart et al., 2001; Plaut et al., 1996; Ziegler et al., 2008; Zorzi et al., 1998); see Figure 1. According to this model, reading begins with orthographic visual analysis. This peripheral reading stage is responsible for letter identification, invariantly for case, size, color, and other visual factors; encoding of letter-position within words; and letter-to-word binding (Ellis & Young, 1996; Friedmann & Coltheart, 2018). Words are then held in a short-term orthographic buffer and, from there, processed along two distinct parallel routes: a lexical and a sublexical route. Reading via the lexical route involves the fast and fluent immediate access of known written words in the orthographic input lexicon to the inventory of the phonological form of words, the phonological output lexicon. The lexical route also includes a branch that connects the orthographic input lexicon to the semantic system, from where information about the meaning of known words is retrieved. Reading via the sublexical route refers to the grapheme-phoneme decoding procedure, which is involved in reading unknown words and pseudowords, and is the initial stage of reading in beginner readers. The outputs of the two routes are held and

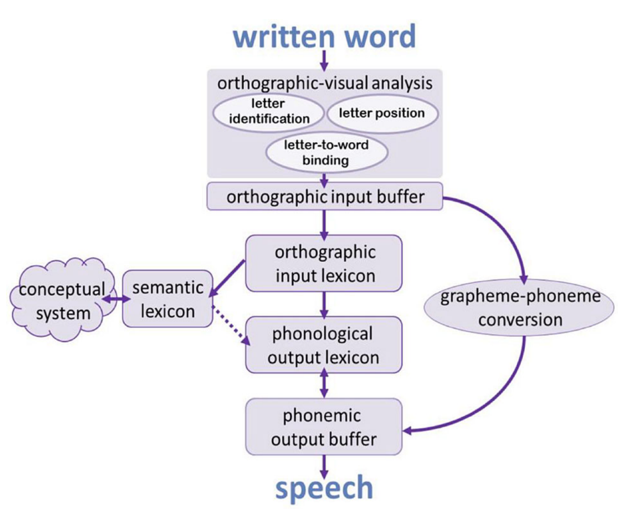

Figure 1. Adaptation of the Dual Route Model (taken from Friedmann & Coltheart, 2018).

assembled in another buffer, a phonological output buffer, until the word or the pseudoword is produced. A computational implementation of the Dual Route model, the Dual Route Cascaded Model (Coltheart et al., 2001) successfully explains various aspects of normal reading behavior of morphologically simple words, including faster reading times for regular words (lexical reading) than for pseudowords (sublexical reading) (Rastle & Coltheart, 1999).

The Dual Route model and the study of dyslexia have had a mutually beneficial relationship. On the one hand, the model provides a tentative map of the different types of dyslexia that may exist. This has benefitted educational research and therapists alike in the common goal of improving screeners and remedial training. On the other hand, detailed reports of individuals with selective deficits, either acquired dyslexia or developmental dyslexia, have been integral to refining the model (Friedmann & Coltheart, 2018). Screeners that adhere to this model test the reading of isolated words and pseudowords. Sentence and text reading are more problematic as a means to identify reading disorders, both because they require additional abilities such as syntax, so a reader with syntactic deficits and no dyslexia may show difficulties in reading aloud such stimuli (Szterman & Friedmann, 2020), and because a dyslexic reader may use the semantic and syntactic context to reduce the number of errors (Friedmann & Rahamim, 2007; Shaywitz, 2003).

The predominance of the Dual Route model to describe expert reading and various types of acquired dyslexias, has also influenced how developmental dyslexia is screened. Several screeners require the reader to read aloud separate lists of regular words, irregular word, and pseudowords, for screeners in English (Castles et al., 2009; Parkin, 2018), French (Jacquier-Roux et al., 2002), or Italian (Zoccolotti et al., 2005). These screeners rely on the architecture of the Dual Route model with respect to the lexical and the sublexical route, and, correspondingly, enable the identification of deficits that differentially affect the lexical or the sublexical route– surface and phonological dyslexia respectively. The logic is that if the locus of impairment is in the lexical path, demonstrating surface dyslexia, the reader will struggle to read irregular words which cannot be read correctly via the sublexical route, but will be able to read regular words and pseudowords correctly. Conversely, in cases of impairment to the sublexical route, causing phonological dyslexia, reading of pseudowords will be impacted because reading can only proceed via the lexicons, where pseudowords are not represented. Still, such screeners are limited in the range of dyslexia types they can identify, because the dimensions of regularity and lexicality that they explore are relevant for surface and phonological dyslexia (and to some aspects of deep dyslexia), but not for developmental dyslexias affecting the orthographic visual analysis stage, such as letter identity dyslexia (Brunsdon et al., 2006), letter-position dyslexia (Friedmann & Gvion, 2001; Friedmann & Haddad-Hanna, 2012; Friedmann & Rahamim, 2007; Güven & Friedmann, 2019; Kohnen et al., 2012), attentional dyslexia (Davis & Coltheart, 2002; Friedmann, Kerbel, et al., 2010a; Hall et al., 2001; Rayner et al., 1989; Shallice & Warrington, 1977), or neglect dyslexia (for examples in Hebrew, see Friedmann & Nachman-Katz, 2004; Nachman-Katz & Friedmann, 2007, 2010). They may also not be sensitive enough for selective deficits in the sublexical route such as vowel dyslexia (Güven & Friedmann, 2021; Khentov-Kraus & Friedmann, 2018) and voicing dyslexia (Gvion & Friedmann, 2010). For these, as further explained below, other types of stimuli should be presented. Moreover, screeners that are based primarily on the number of reading errors, but not on the type of errors made, are limited in their ability to identify various dyslexia types.

Screeners that overlook the rich evidence from case studies in dyslexia research risk misidentifying dyslexia, and in turn, biasing teachers and therapists to provide remediation techniques, such as phoneme awareness training, that do not in fact address the real locus of the deficit for many readers with dyslexia.

2. The Malabi project, a French screener for multiple types of dyslexia

The Malabi Reading Aloud Screener comprises three subtests: 161 single words (ranging from 2 to 8 letters, M = 5.12 SD = 1.29), 40 pseudowords (ranging from 4 to 5 letters, M = 4.88 SD = 0.92), and 44 word-pairs that can be repositioned (consisting of words 2–9 letters long, M = 5.16, SD =1.62). Inspired by the multiple components of the Dual Route model and prior evidence supporting targeted dyslexia identification, this test aims to pinpoint specific reading challenges in French readers by employing suitable stimuli and analyzing reading errors. This method derives from the Tiltan reading battery in Hebrew (Friedmann & Gvion, 2003). Instead of measuring overall accuracy and speed, our French screener, “Malabi – Un outil de dépistage des dyslexies en français” (note the use of dyslexies with an “s”), measures the number of errors of each type made by a given reader. The name “Malabi” was inspired by the delicious dessert enjoyed by the two last authors during the project’s design phase. When the reader shows an abnormal number of errors in one of the predefined categories (reported in scientific literature as characteristic of a certain type of dyslexia), and in the absence of errors outside of the normal range in other categories, we may speak of a selective deficit. To this end, each word in the screener is strategically selected to increase the likelihood of detecting errors characteristic of different types of dyslexia. In particular, the words are chosen so that the relevant type of error yields another existing word, reducing the likelihood of self-correction or of lexical filtering of pseudoword errors. Thus, the Malabi reduces the liklihood of detecting various dylsexias both because it includes stimuli sensitive to various dyslexias and because it involves error analysis.

The Malabi test can be downloaded from the Open Science framework platform (https://osf.io/3pgzb/), including instructions for administering the screener, a guide to the error coding system, and insights into the specific errors measured, along with their scoring methods tailored to distinct dyslexias. Nevertheless, to effectively utilize the Malabi screener, a deep understanding of the various dyslexia types is essential. We strongly encourage researchers and practitioners interested in employing our screener to delve into the literature on different dyslexia types. This will not only aid in comprehending the error coding process but also ensure the screener’s application is both accurate and meaningful. Such informed usage is crucial for maintaining the quality and dependability of research within this field.

Below, we briefly describe the defining performance features of the different types of dyslexias screened for by the Malabi, the hypothesized locus of processing of the underlying impairment, and our selection of stimuli used in the Malabi screener to target the error type. In each case, we give examples of reading errors, but it should be clear that a single error is always ambiguous (for instance, reading bad as dad could arise from letter mirroring, misidentification, repetition, phonological, or neglect errors). Thus, it is the compounding of repeated occurrence of many errors of the same type, at above-chance level, that provides converging diagnostic evidence. In some cases, follow-up screening may be needed to further distinguish be two possible dyslexias, we also describe these cases.

2.1. Attentional dyslexia

Attentional dyslexia is characterized by errors in letter migrations to adjacent words while maintaining the original position within the word of the migrating letter (for example, reading *win fed* as “fin fed”, Shallice & Warrington, 1977). It is thought to result from a deficit in the binding of letters to the words in which they appear, a function of the orthographic-visual analysis system. During reading, multiple words are simultaneously processed (Snell & Grainger, 2019; McConkie & Rayner, 1975), and an orthographic process is applied which binds letters to the word in which they appeared. The term “Attentional dyslexia” was coined by Shallice and Warrington, 1977), who first reported this dyslexia, in an acquired case. They used this term because they suspected that the underlying deficit leading to between-word migrations was attentional in nature. However, later studies revealed that dyslexia and attention can be fully dissociated: attentional dyslexia can appear without visuo-spatial attention deficits, and vice versa (Collis et al., 2013; Keidar & Friedmann, 2011; Lukov et al., 2015). Here, we retain the term “attentional dyslexia” because it is already broadly used, while acknowledging that “letter-to-word binding deficit” or “between-words migration dyslexia” would be more appropriate.

Developmental attentional dyslexia was described in a case of an English reader (Rayner et al., 1989) and its properties were examined in detail in multiple cases in Hebrew (Friedmann, Kerbel, et al., 2010a; Lukov et al., 2015; Toledano & Friedmann, 2023) and in Arabic (Friedmann & Haddad-Hanna, 2014a). These studies describe the types of letter migrations between words that are characteristic of attentional dyslexia: the two most common errors are substitutions with a letter from a neighboring word, and omission of one of the instances of a letter that appears in the same position in the two words.

Another between-word error type that exists but is less prevalent is the addition of a letter (or letters) from a neighboring word, adjacent to a letter in the same position (reading the word pair *page clos* as "plage clos"). Furthermore, these studies found that the majority of letter migrations between words maintain their original position within the new word, relative to word beginning and ending. This is important because it underscores a difference between coding for letter-position within words (which is preserved) and between words (which is impaired). Letters can migrate from words above, below, to the left and to the right of the target word. Importantly for the identification of this dyslexia, Friedmann et al. (2010) found that the likelihood for letter migration is higher when the migration creates an existing word.

In the Malabi, to test for attentional dyslexia we included words pairs that can be read as another existing word through the migration of a letter to the same position in the neighboring word. We included a dedicated subtest of word pairs where all items allow for a possible migration between any two letters at the same within-word position to create an existing word (e.g., *bise vase* can also be read as "bise base", "bise vise", "vise vase" or "base vase", "vise base", all of which are French words). These word pairs were created to be most sensitive to the identification of attentional dyslexia, according to research findings (Friedmann, Dotan, et al., 2010): the words in a pair were of the same length, differed in at least two letters, but also shared at least two letters. In addition, the ordering of the single words in the word list was such that for some of them a position-preserving migration of a letter from the word above or below created another existing word. An error is encoded as a potential migration when an erroneous letter may have come from the same relative position in a word (or pseudoword) that is horizontally located to the right or left of the target word, or vertically, one or two words above or below the target.

2.2. Letter-position dyslexia

Letter-position dyslexia (LPD) is characterized by errors that respect the identity of the letters, but alter their locations within a given word, often resulting in the transposition of adjacent middle letters (e.g., reading *form* as "from", and *stakes* as "skates"). Letter-position dyslexia is therefore thought to arise from a deficit in letter-position encoding, an essential function in the early stage of orthographic-visual analysis whose importance is stressed by the existence of many anagrams such as *density/destiny* or *calm/clam*. LPD was first described as an acquired dyslexia (Friedmann & Gvion, 2001), but cases of selective developmental LPD were then described in readers of Hebrew (Friedmann, Dotan, et al., 2010; Friedmann et al., 2015; Friedmann & Rahamim, 2007, 2014); English (Kezilas et al., 2014; Kohnen et al., 2012); Arabic (Friedmann & Haddad-Hanna, 2014, 2012); Turkish (Güven & Friedmann, 2019), and Italian (Traficante et al., 2021). The deficit has been characterized as a problem of under-specification of the relative positions of middle letters, yielding an elevated rate of errors in both words and pseudowords when they are anagrams of another word (Friedmann & Gvion, 2001; Friedmann & Rahamim, 2007).

Importantly, in letter-position dyslexia, errors occur mainly when the transposition creates an existing word. As a consequence, "migratable" words, i.e., words in which migration of letters within the word create other existing words, are the most sensitive stimuli to detect this dyslexia.

Therefore, to identify letter-position impairments with the Malabi, we included such migratable words in which a transposition of two letters yields another French word. We included both migrations inside the letter string (e.g., reading *signe* as "singe") and migrations involving an exterior letter (e.g., reading *vélo* as "volé"). Because the deficit is thought to happen before either lexical or sublexical processing, we also examined reading of pseudowords. Again, we used migratable pseudowords, which can become words if two letters are transposed (e.g., reading *voclan* as "volcan").

Errors of letter repetition have also been reportedly observed in letter-position dyslexia (i.e., reading *bile* as "bible") or omission of one instance of a letter that appears twice in a word (i.e., the opposite, reading *bible* as "bile") (Friedmann & Rahamim, 2007). These authors hypothesized that when letter-position encoding is impaired, distinguishing two instances of the same letter that only differ in their position becomes difficult, and as a result, those repeated letters may be mistaken to be one, so that one of the instances may be dropped.[1] Therefore, in the Malabi, we included words in which the omission or addition of one instance of a (non-geminate) letter creates other existing words (e.g., reading *montage* as "montagne").

2.3. Letter identification dyslexia

Letter identification dyslexia is characterized by difficulties in reading, manifesting in letter substitutions and omissions, but also including errors in much simpler tasks of single-letter identification, letter naming, and same-different judgments on letters of different cases. Therefore, the deficit is thought to arise from another function of the orthographic-visual analyzer, i.e., abstract letter identification. Very little is known about this as a developmental impairment. One defining feature, however, is that both developmental and acquired cases report that subjects have difficulty matching letters presented in different case as it is the access to abstract letter identity that is impaired (Brunsdon et al., 2006; Perri et al., 1996; Schubert & McCloskey, 2013). Subjects may still match letters of varying sizes which are visually similar. Critically, letter-identification dyslexia as reported in these cases supports a deficit in the mapping of a symbol to its abstract identity as the cases reported had normal performance in visuo-spatial and perception tasks. In some cases of letter identification dyslexia, but not in others, substitutions have been reported as being between visually similar letters (i.e., "p" and "q") (Brunsdon et al., 2006).

To assesses letter identitification dyslexia, the Malabi includes words that are sensitive to this dyslexia—words in which letter substitution can make other words, including some of which also have similar orthographic form (i.e., reading *pire* as "dire"). In the case of suspected letter-identification dyslexia, the Malabi would be followed up with abstract letter identification tasks, such as asking the reader to provide the name and sound of single letters and matching letters of different case. We would also seek to distinguish a pure letter identification dylsexia from poor visuo-spatial acuity, as has been reported in other cases of acquired letter identification dyslexia (McCloskey & Schubert, 2014; Rapp & Caramazza, 1989), with follow-up tasks for multi-digit number reading and bar detection, and ensuring that the reader identifies letters as part of the alphabet and not unfamiliar arrangements.

2.4. Neglect dyslexia

Word-level neglect dyslexia (or "neglexia") has been demonstrated by readers who omit, substitute, and add letters in reading, but their errors predominantly affect one side of the word, usually its left side (i.e., reading *yellow* as "pillow", an example from Ellis et al., 1987). Neglexia is hypothesized to result from a deficit in the orthographic-visual analysis stage, in this case in an orthographic-specific mechanism that biases errors towards either the left or the right side of a word. Neglexia is a pure orthographic deficit, affecting reading exclusively without 'neglect' of other visual stimuli (Friedmann & Nachman-Katz, 2004). In other words, neglexia has been reported in the absence of an underlying spatial attention deficit. Neglexia has been relatively well-documented in adult cognitive neuropsychology (for a review, see Vallar et al., 2010), but few developmental cases with children have been reported (for examples in Hebrew, see Friedmann & Nachman-Katz, 2004; Nachman-Katz & Friedmann, 2007, 2010).

To probe neglexia, the Malabi includes words and pseudowords in which letter omission/substitution on one side creates existing words. We include both words that allow for the identification of left neglect dyslexia (e.g., target word *frime* that may be read as "prime", or *flache* as "lache") and words that allow for the assessment of right neglect dyslexia (e.g., target word *rasé* which may be read as "ras" or *rien* as the word "rie"). Furthermore, we diagnose this dyslexia by comparing the number of errors on the left, middle, and right side of the word. The detection of a potential case of neglect dyslexia should be followed-up by testing to determine whether the significant errors classified as neglect dyslexia result from processing steps involving inadequate allocation of spatial attention. This could impact word reading as well as other tasks that demand sensitivity to spatial sequences of symbol string, such as number reading.

2.5. Orthographic-visual analyzer dyslexia

Orthographic-visual analyzer dyslexia is marked by a diverse array of errors due to its inclusion of various parallel visual processing stages. These errors, while varied, are specific to the peripheral aspects of orthographic -visual processing and include letter omissions, additions, substitutions, and migrations—both within and between words. This condition reflects the complexity of the visual analysis stage, where multiple processes occur simultaneously, leading to the characteristic "mixed-bag" of errors observed. Importantly, the large number of omission, substitution, and addition errors that cannot be attributed to letter-position or attentional dyslexia distinguishes orthographic-visual analyzer dyslexia from attentional and letter-position dyslexia.[2] Furthermore, letter errors made in this category cannot be attributed to selective letter identification dyslexia, as single letter naming is not affected. Case studies of acquired orthographic-visual analyzer dyslexia have been reported, but the evidence is rare in developmental cases (Friedmann & Haddad-Hanna, 2014; Valdois et al., 1995) and in some cases confounded with general visual deficits such as the poor perception of location and orientation of visual stimuli (McCloskey & Rapp, 2000).

Stimuli used in the Malabi that are sensitive to this type of dyslexia are words and pseudowords in which a letter error (omissions, additions, substitutions, and migrations) creates other existing words. Distinguishing this category from letter identification dyslexia is tested through follow-up screening ensuring that identifying individual letters is not problematic, as this ability remains intact in the case of orthographic-visual analyzer dyslexia. To ensure that errors are not consistent with neglect dyslexia, the Malabi also ensures that errors are not relegated to one side of the word or pseudoword. If someone was identified with orthographic visual analyzer dyslexia, follow-up tests would be required to distinguish an orthographic deficit from poor visual perception. It is also neccessary to distinguish this deficit from a phonological output buffer dyslexia (described below), by ensuring that the reader performs normally in language tasks, such as long pseudoword repetition.

To distinguish orthographic-visual analyzer dyslexia from a potential orthographic input buffer deficit (Friedmann et al., 2012; Friedmann & Coltheart, 2018), we have included an array of short and long words, as well as morphologically complex words in our study. Our hypothesis is that morphological errors and a length effect are indicative of an orthographic input buffer deficit, but not of an orthographic-visual analyzer deficit. This distinction should be further explored in a subsequent analysis, by examining the impact of word length on errors if this form of dyslexia is suspected.

2.6. Grapheme-to-phoneme conversion dyslexia (phonological dyslexia)

Readers with phonological dyslexia can fluently read words stored in the orthographic lexicon but have difficulty reading novel or pseudowords, even if they are monosyllabic (see the developmental case study of Campbell & Butterworth, 1985). Thus, this deficit is thought to arise from a faulty sublexical route, during grapheme-to-phoneme conversion. Because phonics instruction is often the first step to literacy, phonological dyslexia generally makes learning to read difficult and slow, and words must be memorized by their visual form (Castles & Coltheart, 1993). Phonological dyslexia was first discussed in the case of a participant with dyslexia who was able to read familiar words fluently, but unable to read pseudowords despite of an intact ability to orally repeat and write spoken items (Beauvois & Derouesne, 1979).

To detect phonological dyslexia in the grapheme-to-phoneme conversion route, Malabi includes pseudowords with single and multi-letter regular grapheme-phoneme correspondences. Pure grapheme-phoneme conversion dyslexia is identified if the reader's errors reach threshold on the pseudoword test, but not on the existing words subtests. Furthermore, identifying this dyslexia requires that errors are not due to migrations or negelct dyslexia. To reject neglexia, errors should not involve the omission, addition, or substituion of a letter (making a new word) to a consistent side. To differentiate grapheme-phoneme conversion dyslexia from phonological output buffer (see next description), the list includes many short regular morphologically simple pseudowords. Additionally, a follow-up test of pseudoword repetition would assess the involvement of the phonological output buffer in the deficit.

2.7. Phonological output buffer dyslexia

The key feauture of the reading of individuals with phonological output buffer is difficulty in reading aloud long pseudowords, as well as long and morphologically complex words. Because the phonological output buffer is involved not only in reading aloud but also in speech production, individuals with a deficit in this stage also show similar difficulties in oral production tasks such as repetition of the same types of long stimuli. They have also been reported to substitute numbers and function words with other words from the same category (Dotan & Friedmann, 2015). The same has been reported for developmental cases in Hebrew (Guggenheim & Friedmann, 2014). The theory underlying these errors, as reported by the authors, is that the phonological output buffer results in errors at the level of the phonological unit. The phonological output buffer is organized into "storage-units" comprising pre-assembled phonological units of various sizes, ranging from single phonemes to entire morphemes, function words or number words (Dotan & Friedmann, 2015).

Traditionally, a deficit in reading pseudowords was thought to result from a deficit in the grapheme-phoneme conversion procedure. However, it has been shown that a deficit in pseudowords may occur in the absence of a deficit in the conversion itself, but rather due to a deficit in an output stage of reading aloud, common to speech production: the phonological output buffer that holds phonological units until their production and assembles phonemes and morphemes into a word (Guggenheim & Friedmann, 2014).

We screen for this type of dyslexia in the Malabi by asking for reading aloud of long pseudowords (to distinguish from errors in reading short pseudowords, which may be a sign of poor grapheme-phoneme conversion, see grapheme-to-phoneme conversion dyslexia). In the single word reading test, we also included morphologically complex, function, and number words. If phonological buffer dyslexia is suspected by the results of the Malabi, a precise identification requires that we follow up by looking at length effects on pseudoword errors or testing for evidence in speech production tasks including repetition and phonemic awareness.

2.8. Vowel dyslexia

Recently, a selective deficit in reading vowel letters within pseudowords was documented, termed "vowel dyslexia" (Güven & Friedmann, 2021; Khentov-Kraus & Friedmann, 2018). Vowel dyslexia is characterized by migrations, omissions, additions, and substitutions of vowel letters in reading aloud, without parallel errors in reading consonant letters. Vowel dyslexia is thought to result from a vowel-letter-selective deficit in the sublexical route, because the vowel errors occur only in pseudowords. Individuals who also have surface dyslexia, in addition to vowel dyslexia, are forced to read existing words through the sub-lexical route, so they may make vowel letter errors in existing words as well. Vowel dyslexia is diagnosed when a participant makes significantly more vowel errors in comparison to the controls, but not more consonant errors than the controls, and when this vowel–consonant difference is significant (e.g., yields a classical dissociation in comparison to the control group using the Crawford and Garthwaite dissociation test, Crawford & Garthwaite, 2005). Individuals with vowel dyslexia do not demonstrate difficulty in vowel phoneme manipulation in oral language tasks (Khentov-Kraus & Friedmann, 2018; Güven & Friedmann, 2021).

Stimuli that are most sensitive to detect vowel dyslexia, and which were included in the Malabi, are pseudowords in which a vowel error creates an existing word (e.g., reading *flache* as "flèche"), and in case the participant also has surface dyslexia (which is quite common), also in words in which vowel errors create other existing words (e.g., reading *fille* as "folle").

2.9. Surface dyslexia

Surface dyslexia refers to an impairment in the lexical route, which causes the reader to overly depend on sublexical reading, even for reading existing words. Surface dyslexia may result from impairments in different components and connections of the lexical route (Friedmann & Lukov, 2008, 2011), but in reading aloud all these variants show similar patterns. Their outcome is a difficulty in reading words whose pronunciation is not fully predictable by conversion from orthography to phonology, including words that have multiple options for conversion, and irregular words that are not read according to the GPC rules or that are read according to infrequent grapheme-phoneme combinations. Reading such unpredictable words sublexically causes regularizations (e.g., pronouncing the t in *listen*, reading *door* to rhyme with *poor*). Especially sensitive to these words are potentiophones, words that, when read sublexically, create other existing words (e.g., reading *now* to sound like "know"). Pseudoword and predictable regular word reading is unaffected in cases of pure surface dyslexia. Slow reading is also characteristic of surface dyslexia, but it is neither specific to nor does it apply to all cases of surface dyslexia. In highly transparent languages, there are fewer unpredictable words, but it is stil possible to identify surface dyslexia using target words that yield regularization errors, for example with respect to stress position (Traficante et al., 2011, 2021, for Italian), and vowel length and properties of consonants (Güven & Friedmann, 2019 for Turkish). Slow reading is also characteristic to surface dyslexia, but it is neither specific to surface dyslexia, nor does it apply to all cases of surface dyslexia (Guven & Friedmann, 2022).

There is ample work and reports on developmental surface dyslexia across many languages with non-transparent orthographies, such as English (Castles, 1996; Castles & Coltheart, 1993), French (Valdois et al., 2003), Hebrew (Friedmann & Lukov, 2008; Gvion & Friedmann, 2016), and Arabic (Friedmann & Haddad-Hanna, 2014a), as well as in languages with more transparent orthographic codes, such as Italian (Zoccolotti et al., 1999), Spanish (Jiménez et al., 2009), Filipino (Dulay & Hanley, 2015), Greek (Sotiropoulos & Hanley, 2017), and Turkish (Güven & Friedmann, 2022). French is an intermediate language in terms of transparency, being quite irregular in spelling (i.e., there are many possible spellings for a given sound), but rather regular in reading (there are relatively few pronunciations for a given sequence of letters). Nevertheless, many frequent but irregular words exist in French. We used such unpredictable irregular words in the Malabi to test for surface dyslexia (e.g., *femme* pronounced /fam/, not /fEm/).

2.10. Deep dyslexia

Deep dyslexia is thought to result from deficits in both the lexical route (in the path linking the orthographic input lexicon and phonological output lexicon) and the sublexical route (Ellis & Young, 1996). As a result, readers with deep dyslexia read via the semantic lexicon which is itself possibly imprecise. They identify a word, understand its rough meaning, and then attempt to name what they have understood, a cumbersome procedure that results in semantic errors. Because reading proceeds via meaning, the hallmark of deep dyslexia are surprising reading errors in which responses are erroneous, but in the right ballpark for meaning (e.g., reading *sand* as "beach"). Pseudoword reading is also greatly impaired as these items cannot be accessed by meaning. It has been postulated that reading via meaning is facilitated for words that have well-defined perceptual dimensions or highly imageable content, thus explaining the reported difficulties in reading abstract and function words (Coltheart, 1981; Marshall & Newcombe, 1973). Developmental deep dyslexia, which is relatively rare, has been reported in English (in children with Williams Syndrome, Temple, 2003, 2006), in Japanese (Yamada, 1995), and in Arabic (Friedmann & Haddad-Hanna, 2014). In addition to semantic errors, morphological and visual errors are frequent in deep dyslexia, as well as difficulty with abstract and function words.

Included in the Malabi are words that are easy to conceptualize as well as abstract and function words, along with morphologically complex words. In the error analysis of the Malabi, we code for semantic errors (i.e., reading *library* as "book"). If this dyslexia is suspected by semantic errors in the existing words subtests, we follow-up by assessing the errors made on the pseudoword test, and single word reading of abstract and function words, and morphological errors.

3. Experimental study: General approach and method

The goal of the current project was to assess if the Malabi screener could detect selective types of reading deficits. To this aim, we established norms for the test and used them to detect the first cases, to our knowledge, of developmental attentional dyslexia and letter-position dyslexia in French. We provide an in-depth analysis of the factors that modulate the deficit for these readers, and confirm a double dissociation between the two dyslexias. This research was carried out in two phases:

- **Experimental screening.** We first established Malabi norms for the different error categories made by 141 normal readers in middle-school 6th and 7th graders. In France, middle-school begins in the American equivalent of 6th grade. We chose middle-school to ensure a population that should have had enough years of schooling to have mastered the alphabetic code of French and have a large orthographic lexicon, therefore limiting the number of errors due to lack of reading experience. Relative to those norms, we then screened sixteen 6th and 7th graders from a specialized learning disabilities school with the Malabi. We present the results of this dyslexic population and focus on the students that appear to have a selective type of dyslexia. Traditional tests for dyslexia screening in France were also used to assess their phonological abilities.

- **Experimental investigation**. Upon identifying potential cases of selective attentional or letter-position dyslexia using the Malabi screener, we implemented a secondary testing protocol. This subsequent round of testing employed a specialized battery of tests, each expressly designed to diagnose either attentional or letter-position dyslexia. The aim was to validate the initial diagnoses. The underlying rationale is that while the Malabi screener presents a limited number of words that might elicit errors, a longer and more detailed test, focused solely on one specific type of error, should provoke a significantly higher number of mistakes from individuals with the selective dyslexia, compared to normal readers and subjects with a different dyslexic impairment. This amplification of error occurrence provides a more robust diagnostic confirmation for either attentional or letter-position dyslexia. Furthermore, using these additional word lists we were able to examine in more detail the properties of these dyslexias and their manifestation in French, and the dissociation between attentional dyslexia and letter-position dyslexia.

Method

3.1. Participants with developmental dyslexia

Our dyslexic participants all came from CERENE (www.cerene-education.fr), a specialized school for children with normal IQ who have developmental learning disorders (dyslexia, dyspraxia, dyscalculia, etc.), located in Paris, and providing 2nd–8th grade education. Our reason for working with this school was to exclude dyslexic readers with other cognitive or environmental confounds that could influence our measures. Admission to CERENE requires a stringent neuropsychological assessment to ensure normal IQ and specific understanding of the student's profile. The school provides high-quality education through trained teachers for learning disorders, small classes, and adaptive tools to help students compensate for their deficit (i.e., electronic readers that use larger font with spacing and highlighting, audio instructions, explicit step-by-step instructions, etc.). Testing students at CERENE thereby provided us with a sample of readers whose difficulty could not be due to low intelligence or insufficient reading instruction and practice. The school referred sixteen students to our research team, with seven from 6th grade and nine from 7th grade. All these students were native speakers of French and in a normal age range for their grade.

3.2. Control group for establishing screener norms

For the control sample, 141 students participated, none of whom were receiving special help in language or reading skills, as reported by the school director. These students came from six classes in two middle-schools and included 77 6th graders (age range 11;3–13;0) and 64 7th graders (age range 12;3–15;2). Both schools were situated in lower to middle socio-economic areas, in towns about an hour outside of Paris. Three students in 6th grade and three students in 7th grade were removed because their age was greater than 2 standard deviations from the mean. 51% of 6th graders and 34% of 7th graders reported speaking another language at home than French, but school administrators confirmed that all students had been in the French school system for over four years (our minimum criterion for inclusion).

3.3. Procedure

All parents of the students from the participating schools were sent a letter explaining the study and given the possibility of opting out if they or their child do not agree to participate. Each participant was tested individually in a quiet room in the school. The testing was carried out over a 3-month period at the end of the French school year. Reading errors were phonetically noted. For each type of reading error, an error type was attributed by agreement between three researchers in the project and put into a database (explanations of the error types and examples from the test are given in the Appendix). This method allowed us to semi-automate the error-coding process, meaning that once an error had been made by one participant and included in the database, we could automatically attribute it to other cases.[3] In some cases, an error could be attributed to more than one error type, for example, reading the word pair "puis sois" as "suis sois" could be labeled as a migration between words or as letter-doubling within the word. In such cases, the error type was categorized using both labels as an "either or" error. Our logic was that if a reader has a selective deficit, they will make many more mistakes of a particular type, so those ambiguities will be lifted by compiling data from multiple errors. For example, if the reader makes significantly more migrations between words than the controls, and does not make other letter-migration type errors (letter-transposition within words or doubling errors), we may conclude that the deficit is attentional dyslexia rather than letter-position dyslexia. This will also be supported by an error pattern that includes omissions of letters that appear in the same position in the two words but not of other letters.

4. The Malabi screener

The three subtests of the Malabi reading aloud screener were printed on paper in 14pt Calibri font, with vertical double spacing between words. No time limit was imposed during testing, but children were timed and told to try and read quickly but accurately. They were also instructed to not use their finger to guide their reading. If a student did this instinctively, they were immediately asked to remove their finger. A short break was taken between the tests. The three tests were presented in a fixed order (single word, pseudoword, word-pair reading). No response-contingent feedback was given during reading, only general encouragement. On average, with time for explanations, the test takes 12 minutes for normal readers in the 6th and 7th grades. Time to take the test for children with dyslexia varies greatly depending on the severity of the deficit.

4.1. Establishing norms

For the control group, we calculated, for each of the error types, the mean number of errors and standard deviation. Participants who made a number of errors that was more than 3 standard deviations away from the mean in any particular error-type or in their total number or reading errors, were removed from further calculation of the control group norms. According to this criterion, 13 participants were excluded from the control group.[4] To ensure comparability among control participants from both participating schools, we conducted a mixed analysis of variance, considering subtest types, grade levels (6th, 7th), sex, and school as factors. We report significant effects at alpha = 0.05. A significant main effect of grade, $F(1, 114) = 6.16$, $p = .01$, revealed lower error rates in 7th grade (average percent error in 6th grade = 4%, SD = 2%; 7th grade = 3.5%, SD = 2%). An interaction between school and sex, $F(1, 114) = 11.75$, $p < .001$ showed that in 6th grade, the girls in school 2 made more errors than boys on one subtest, the single word test. All error rates were within 1SD of the other, precluding the removal of subjects to create equal score groups by grade and sex.

For the comparison of the rates of different error types between grade 6 and grade 7, and in order to reduce the false discovery rate, we used the following approach: we summarized the total number of errors across subtests for each participant, and conducted a comparison between grades for a dyslexia type only when the average total number of errors across the three subtests was 2 or above, or when the mean number of errors in one subtest exceeded 1. We used false discovery rate (FDR) analysis (Benjamini & Hochberg, 1995) at alpha = .05. This analysis showed that between grades, error rates approached being significantly different for surface errors on the single word test ($p = .016 >$ critical value $= .006$), which makes sense as the orthographic lexical knowledge accumulates with time. For the other error types we found no significant difference, suggesting that whereas the lexicon is still being built in sixth grade, other decoding skills have plateaued after many years of school and reading experience.

After removal of outlier subjects, a new mean and standard deviation were calculated, providing our normed data. For each dyslexia type, we then computed the threshold number of errors a reader would have to make to be significantly below the control group ($p < .05$) (i.e., to make significantly more errors of this type compared to the control group). This comparison was done using a Crawford & Howell's and Crawford and Garthwaite's t-test for the comparison of an individual to a control group

Table 1. Retained normal control results for each of the grades on the three Malabi subtests: single words, pseudowords and word pairs.

	6th graders (N = 68, 31 female, age 11;3–12;8)			7th graders (N = 54, 18 female, age 12;3–13;4)		
Error types: ***Threshold*** Mean (SD)	Single Words N = 161	Pseudowords N = 40	Word pairs N = 88	Single Words N = 161	Pseudowords N = 40	Word pairs N = 88
Total	11.6 (7.93)	4.03 (3.50)	3.87 (2.83)	8.30 (6.58)	3.57 (3.26)	2.72 (2.54)
Attentional	***3*** 0.65 (1.18)	***2*** 0.21 (0.54)	***6*** 2.52 (1.98)	***3*** 0.67 (0.95)	***2*** 0.33 (0.73)	***5*** 1.83 (1.55)
Letter-position	***6*** 2.00 (2.19)	***6*** 1.93 (2.18)	***2*** 0.12 (0.33)	***5*** 1.22 (1.89)	***6*** 1.74 (2.03)	***2*** 0.07 (0.38)
Left Neglect	***2*** 0.04 (0.21)	***2*** 0.02 (0.12)	***2*** 0 (0)	***2*** 0.02 (0.14)	***2*** 0.0 (0.0)	***2*** 0.0 (0.0)
Right Neglect	***2*** 0.38 (0.65)	***2*** 0.09 (0.29)	***2*** 0.09 (0.29)	***2*** 0.43 (0.77)	***2*** 0.04 (0.19)	***2*** 0.04 (0.19)
Orthographic Visual analyzer, Letter Identification dyslexia	***2*** 0.43 (0.65)	***3*** 0.75 (1.20)	***2*** 0.28 (0.49)	***2*** 0.35 (0.59)	***2*** 0.43 (0.66)	***2*** 0.17 (0.38)
GP conversion		***3*** 0.87 (1.01)			***3*** 0.74 (0.94)	
Phonological buffer (morph.)	***3*** 0.88 (1.11)		***2*** 0.10 (0.31)	***3*** 0.59 (0.98)		***2*** 0.11 (0.32)
Vowel	***3*** 1.01 (1.14)	***2*** 0.16 (0.37)	***2*** 0.10 (0.31)	***3*** 0.54 (0.95)	***2*** 0.30 (0.60)	***2*** 0.06 (0.23)
Surface	***13*** 6.12 (4.03)			***11*** 4.43 (3.61)		
Deep (semantic)	***2*** 0.04 (0.21)		***2*** 0.02 (0.12)	***2*** 0.06 (0.23)		***2*** 0.0 (0.0)

We provide the mean and standard deviation for each error type. Notably, the threshold for impairment is highlighted in bold and italicized text. This threshold signifies the minimum number of errors of a specific type that is already significantly higher than the control group, as determined by Crawford and Howell's one-way t-test for single-case versus control comparisons ($p < .05$). To ensure robustness, we opted not to consider a single error as indicative of a significant deficit. Therefore, in instances where the statistical analysis indicated a threshold of 1 for determining impairment, we adjusted it to 2. Letter Identification dyslexia would additionally be identified by the participant's inability to complete a letter name and sound task after reaching the threshold in the Orthographic Visual Analyzer task on the Malabi. For Deep dyslexia, the (semantic) refers to the fact that we only counted errors where the reader proved a totally different word of the same category (i.e., reading 'croissant' for the word 'boulangerie').

(Crawford & Garthwaite, 2007; Crawford & Howell, 1998). Sample demographics for the retained controls are in Table 1.

4.2. Screening for selective deficits with the Malabi screener, and principles to determine dyslexia type

We defined a selective dyslexia when a student made significantly more errors in one of the ten error types established by the normed data, in the absence of a greater number of errors than the controls of another error-type. Only one exception was made to this rule: the frequent case of a large number of surface dyslexia errors in concert with another type of error. Surface errors are due to inability to read words via the lexical route, which results in over-reliance on grapheme-to-phoneme conversion via the sublexical route, which leads to regularizations. Inefficient lexical route reading could either result from dyslexia following a deficit in the lexical route, or from lexicons that are not fully-established, which could be a result of insufficient exposure to effective reading, which typically builds up the mental lexicons. Given that most children with various kinds of dyslexia develop strategies to avoid reading, surface errors may also results from a lack of adequate reading experience secondary to another type of dyslexia, as opposed to being a genuine case of surface dyslexia.

Here we will describe our approach for identifying a selective dyslexia based on the thresholds established for the three subtests outlined in Table 1. It is important to note that not all three tests were relevant for every dyslexia type, and furthermore, not all types of dyslexia were observed in our dataset. In each case, the diagnosis was based on a reader making a significantly larger number of errors of the relevant type, in the relevant stimulus list than the control group.

A participant was diagnosed with **attentional dyslexia** if, on the word pair test, they made a significant number of between-word migrations (e.g., reading *dure pire* as "dire pure"), omissions (e.g., reading *dure pire* as "due pire"), or additions (reading *aire pile* as "paire pile") that could be explained by a neighboring word (two words vertically or horizontally from the target). If a significant number of between-word errors were made on the word-pair test, we followed up by looking for vertical between-word migrations on the single word and pseudoword tests.

Letter-position dyslexia was diagnosed when the reader made within-word transpositions that involved two letters on the single word and the pseudoword test (the word pair test was not designed to include words with possible within-word letter transpositions). Also included in letter-position dyslexia errors were errors of letter repeating or removing of one instance of a double consonant. Double letters that make a single phoneme were not included in this category.

Letter Identification Dyslexia was diagnosed when the reader showed more errors than controls on omissions, additions, and substitutions that could not be attributed to a transposition or migration, and which was not specific only to consonants or to vowel letters, and affected both words and pseudowords. However, to distinguish these errors from a potential orthographic visual analyzer deficit, these cases would require follow-up testing of single letter identification. We did not have any of these cases in our sample, but we recommend in case of suspected letter identity dyslexia in the MALABI, to also test the reader's ability to tell name and sound of single letters, and to test finding same letters in different cases.

Left or right **neglexia** was diagnosed when a reader produced errors on a single side of words that could not be explained by within or between word migrations or a misreading due to the regularization of letter sounds, and had a within-normal rate of errors on the middle and on the other side of the word.

Orthographic-visual analyzer deficit (or possibly orthographic input buffer dyslexia) was identified when a subject made a significantly higher number of errors than typical readers of consonant omissions, additions, and substitutions that could not be attributed to a migration. Also reaching error thresholds for both within-word and between-word consonant migrations was not deemed a disqualifying factor for a diagnosis of selective dyslexia in this category. The distinction between an orthographic-visual analyzer deficit and an orthographic input buffer deficit was based on the presence of morphological errors and a length effect. We hypothesize that these characteristics may be indicative of deficit in buffer functions, but not necessarily of orthographic-visual analyzer deficits.

It should be noted that for attentional, letter-position and orthographic-visual analyzer dyslexia, we calculated threshold errors separately for consonants and vowels to ensure that our dyslexic participants' errors specifically reached threshold for consonants. Previous papers on vowel dyslexia have demonstrated that vowel dyslexics may also make these types of errors (Khentov-Kraus & Friedmann, 2018). **Vowel dyslexia** was diagnosed when a participant made significantly more vowel in comparison to consonant letter errors than the controls (omission, substitution, addition, vowel transpositions, and vowel migrations between words), which could not be attributed to letter-position dyslexia or attentional dyslexia. Voxel dyslexia is identified as a sublexical reading impairment, thus these mistakes were examined within the subtest of pseudoword reading. However, dyslexia tends to manifest as a prolonged dependance on decoding processes that can result in notable vowel mistakes during word reading as well.

Surface dyslexia was detected by a greater number of errors than controls in reading irregular, potentiophonic, and unpredictable words (only single word test). For example, French readers might read the very common word "*parfum* /paʁ.fœ̃/" as "*par* /paʁ/, *fum* /fym/", an existing French verb.

Grapheme-phoneme conversion dyslexia (phonological dyslexia) was diagnosed when the reader made a greater number of errors than controls in reading pseudowords. Errors include omission, substitution, addition and migration of letters in the pseudoword, as well as impaired multi-letter conversion.

Phonological output buffer dyselxia was identified when the reader made a greater number than controls of morphological errors on words with complex morphology, function-word substitutions, as well as more errors on longer than shorter words, and increased number of errors in reading pseudowords in comparison to morphologically simple words. Identification had to be followed up by accompanied impaired non-word repetition tasks.

Deep dyslexia was diagnosed when the reader made a larger number of semantic errors than controls. For deep dyslexia, if the participant made semantic errors, we continued and assessed whether they also made morphological errors, substitutions of function words, and visual errors, also characteristic of deep dyslexia. We also assessed whether their pseudoword reading was especially hampered.

Only 2% of responses could not be categorized by our scheme. A detailed description with charts for how to use our coding scheme to detect different dyslexias is available here, https://osf.io/3pgzb/).

4.3. Additional traditional tests used in dyslexia screening in France

We also asked all of our dyslexic participants to take the following traditional screeners for dyslexia. Our controls did not do these tests as they are already standardized by grade.

4.3.1. Alouette

We used the "Alouette" reading test (Lefavrais, 2005), commonly used in France for dyslexia screening. This test requires reading syntactically well-formed nonsense text with rare words (e.g., translated extract: "And when the evening descends, when the amethyst of the sunset plays, the sky blushes its waters."). Participants are asked to read quickly and accurately in 3 minutes. Scores combine words correctly read and time, compared to grade-level standards.

4.3.2. Oral language and phonological awareness

To assess oral language, phonological working memory, and phonological awareness, we used a pseudoword repetition task and two phoneme manipulation tasks from the Odédys dyslexia test battery (Jacquier-Roux et al., 2002). The pseudoword repetition task included 20 items with 2–5 syllables. In the first phoneme manipulation task, participants removed the first phoneme and stated the new word (for the word "brame", respond "rame"). In the second task, they combined the first phonemes of two words to form a syllable (for the words "photo—artistique", respond "fa"). Each of the phoneme manipulation tasks had 10 items, and number of correct responses were recorded. Two practice trials with feedback were given before the actual task.

5. Readers with selective kinds of dyslexia: results

5.1. The Malabi identified readers with attentional dyslexia, letter-position dyslexia, and surface dyslexia

To identify which of the students in the learning disability school has dyslexia, and for those who have dyslexia, to identify the dyslexia type, we compared the performance of each participant from the learning disability school to the control group. We used Crawford and Howell and Crawford and Garthwaite's t-test for the comparison of an individual to a control group (Crawford & Garthwaite, 2007; Crawford & Howell, 1998), with $p < .05$. The comparison included the total number of errors, as well as the number of errors characteristic of each dyslexia type.

Among the 16 students tested from the learning disability school, 12 were diagnosed with various forms of dyslexia using our comparison procedure. Four participants demonstrated reading skills within the normal range for all error types. Out of the 12 children with dyslexia, seven met the threshold criteria, indicating a specific pattern corresponding to one of three developmental dyslexia types not previously reported in French. Specifically, LP, TR, and LD passed the threshold for attentional dyslexia, while JB and PO exhibited symptoms of letter-position dyslexia, with JB also showing vowel dyslexia. HW showed characteristics of phonological dyslexia, and JC displayed symptoms of surface dyslexia. Five other participants presented with combinations of multiple dyslexia types, displaying above-threshold error rates across various dyslexia categories. As this article's focus is on detecting and describing selective dyslexia, we will provide a more detailed analysis of the performance patterns of the seven participants with selective deficits, including their specific number of errors for each dyslexia type, as presented in Table 2. Below we describe the selective cases in terms of standard deviation from the control mean, when scores reached threshold for an error type.

Table 2. Types of errors and the number of errors made by the seven participants exhibiting selective dyslexia in the Malabi screener.

	Dyslexias						
	Attentional	Letter-position	Orthographic Visual Analyzer	GP Conversion	Phonological Buffer	Vowel	Surface
Types of errors	Migrations between words	Migrations within words	Consonant—omission, addition, substitution		Morphological errors	Vowel—omission, addition, substitution	Regularizations
Tests of interest	Word pairs	Single words, Pseudowords	Single words, Pseudowords	Pseudowords	Single words, Word pairs	Single words, Pseudowords	Single words
Subj: sex, grade, age in months							
LP: m, 6, 152	6*	3, 5	0, 2	2	0, 0	0, 0	13*
TR: m, 7, 139	12*	3, 8	0, 1	0	1, 0	0, 0	6
LD: f, 7, 145	10*	0, 4	0, 2*	0	2, 0	0, 0	7
JB: m, 6, 151	3	13*, 11*	1, 0	2	1, 0	3*, 1	9
PO: m, 7, 142	3	14*, 10*	0, 1	1	1, 0	1, 1	11*
HW: m, 7, 144	4	1, 9*	0, 0	3*	1, 0	1, 0	9
JC: m, 6, 147	4	4, 1	0, 2	1	2, 1	2, 0	18*

Neglect and Deep dyslexias were absent for all participants and are therefore not reported here. Additionally, the category of Letter Identification dyslexia, while not detailed in this table, would have been suspected for any student who reached the threshold on the Orthographic Visual Analyzer test. This would necessitate subsequent testing for single letter identity.The errors included in the categories of omission, addition, substitution, and morphological errors are exclusively those that could not be explained as migrations occurring either between or within words.
*Errors that were significantly more frequent in the participant group compared to the control group using Crawford and Howell's and Crawford and Garthwaite's t-test for the comparison of an individual to a control group (Crawford & Garthwaite, 2007).

5.1.1. Participants with attentional dyslexia

TR, 7th grade. TR made many between-words migration errors, equivalent to 6.76 SD above the control group on the word pair test, 75% of these errors were of a consonant and 25% involved a vowel. Letters migrated from both right to left (reading *aime armé* as "arme aime") and left to right (reading *litre vivre* as "litre vitre"). Further evidence of attentional dyslexia was found in the single word reading test, where his between-words migration errors reached threshold criterion and were 2.45 SD above the control mean. All other error types were otherwise within the normal range. Interestingly, and below threshold, he made 6 errors that could be scored as surface errors (e.g., reading *base*, /baz/ as "basse", /bas/), but could have actually been classified as migrations of a letter from a neighboring word rather than from an overregularization of the letter sound. For instance in the *base* -> "basse" case, the additional letter "s" could have originated from the word *rose* written two lines above the target word. This mistake in reading did not appear to stem from not knowing the rule converting a single "s" to a /z/phoneme, as he correctly made the /z/ sound in other words with "s" when there was no neighboring word with an "s" in the same position.

The pseudoword test was not actually designed for between-word migrations. Nevertheless, TR misread 14 items (35% of the pseudowords he read), and 8 of these errors could be a result of between-word migrations, equivalent to 10.50 SD above the control mean.

LP, 6th grade. LP had significantly more between-word migrations than the controls, in word-pair reading his between-word migration rate was 1.76 SD above the control's mean. 100% of these errors consisted of a consonant migration. Between word migrations was the only type of error that was significantly higher than the controls. His between-word migrations included typical attentional pairs such as reading *fend rond* as "rend rond" and *cape page* as "cage page". Migrations were made from the right to the left word as well as vice versa. Analysis of his single word test responses also reached threshold for attentional errors, 1.99 SD above control mean. In the single word subtest, he also reached threshold for surface errors, however these errors all included misreading rule-based graphemes-phoneme sounds (1.71 SD above the control mean), indicating that he was reading real words via the sublexical route and making conversion errors in them. For example, this student appeared to have not learned that the single letter "s" between two vowels is pronounced /z/ and not /s/. As he had no errors on the irregular words (i.e., parfum, femme, etc), it does not appear that he had surface dyslexia, but just less experience than needed to fully integrate the orthographic rule.

LD, 7th grade. LD's reading appeared fluent and easy, but her reading errors in the word-pair reading task revealed that she had attentional dyslexia: she made significantly more between-word migrations than the controls, with a score at 5.27 SD from the mean in word pairs and 3.5 SD in the single word list (and 3.7 SD above the mean in pseudowords). 70% of these errors were consonant migration, 30% involved a migration of a vowel. Horizontal migrations in word pairs reflected errors from letters moving from the right word to the left (e.g., *fous tour* was read as "tour four") and vice versa (*masse cesse* was read as "masse casse"). Errors included reading *varie* as "marie", where the "m" migration plausibly came from the word *morte* two lines above and reading *rasé* as "rusé", the "u" from the word "ruse" written one line above. LD also made 2 consonant errors (reading *glad* as "glab"; *fotre* as "fot") in the pseudoword test that could not be attributed to attentional dyslexia. These 2 errors put her exacly at threshold. However, in single word reading, she did not make any errors of substitutions, ommisions or additions in the word list that could not be attributed to attentional errors. No other error types were made in a rate that was significantly above the controls'.

5.1.2. Participants with letter-position dyslexia

JB, 6th grade. JB had a selective letter-position deficit. He made a large number of transposition errors (e.g., *magner* read as "manger"; *patrie* read as "partie", *cirer* read as "crier"), which was significantly larger than that of the controls. In reading single words his transposition rate was 5.50 SD above the control mean. 45% of transpositions involved only consonants, and 55% involved a transposition with at least one vowel letter. In pseudoword reading, too, JB made significantly more transpositions than the controls (4.16 SD above the mean). 62% of these errors were of consonant transpositions and 38% contained at least one vowel. In reading pseudowords, he also made 3 multi-letter grapheme-phoneme conversion errors, putting him exactly at threshold (2.11 SD above the control mean). Two of these errors were of misinterpreting the "s" sound /z/ when sandwiched between vowels and pronouncing the g in its less frequent /Z/ sound. Given that he did not make this error when reading real words, we can deduce that his dyslexia has made him less familiar with these rule-based sounds when he cannot rely on his orthographic lexicon.

One important point regards the identification of vowel dyslexia in the presence of letter-position dyslexia, and identifying when vowel letters are a result of letter-position dyslexia rather than of vowel dyslexia. When we look at the total number of JB's vowel errors in single words, he made a total of three vowel errors, which is significantly higher than the control rate of vowel errors. However, some vowel errors could result from letter-position dyslexia: errors of a transposition of a vowel and a consonant, errors of transposition of two vowel letters, and errors of doubling of a vowel letter or omission of one instance of a vowel letter that appears twice. In the case of JB, when we look at the types of vowel errors he made, only one error was not of these kinds. Furthermore, when we compare the rate of transpositions and doubling/omissions that involved a vowel and those that involved only consonants, we see that the rates are similar: transpositions and doubling/omission that involved a vowel letter were 47% of letter transpositions in the single words test, and 58% in the pseudoword test.

PO, 7th grade. PO also made a very large number of transpositions. He was 6.8 SD greater than the control mean in single words, and 4.1 SD greater in pseudowords, subtest. Transpositions that involved two consonants (e.g., reading linge as ligne) were 43% of the transpositions in single words and 40% of the transpositions in pseudowords. He also made 11 surface errors which reaches Crawford's significance for this error type (1.82 SD above the control mean).

The word-pair list did not include migratable words, and therefore was not sensitive to letter-position dyslexia. And indeed this subtest was not sensitive to the letter-position dyslexia of JB and PO. Both of them did not produce a significant number of errors in any of the categories on the word-pair list.

5.1.3. Grapheme-phoneme conversion impairment

HW, 7th grade. HW's word reading of real words was relatively fluent. When he read existing words, none of the error types reached significance. In contrast, his reading of pseudowords was markedly strained, with a significant number of letter transposition errors (3.58 SD above the control mean) and of incorrect multi-letter conversion (2.42 SD above the control mean), in which he converted letters without taking into account multi-letter conversion rules. Letter-position errors that occur only in pseudowords, alongside additional difficulties in pseudowords, cannot be a result of letter-position dyslexia, which affects both pseudowords and (migratable) words. HW's error pattern indicates a difficulty in the sublexical route, either at the level of the phonological output buffer or the grapheme-to-phoneme conversion route. Given HW's success on the pseudoword repetition and the phonological manipulation tasks, (see upcoming section, **Dyslexia, but no phonological impairment)** it seems that his deficit results from a deficit in grapheme-to-phoneme conversion.

5.1.4. Surface dyslexia

JC, 6th grade. JC made many surface errors, namely, reading errors that indicate that he was reading existing words via the sublexical, instead of the lexical, route. On the single word reading test, which included 97 unpredictable words, JC's rate of surface errors was 2.95 SD above the control mean. JC's surface dyslexia occured in the absence of a phonological impairment as his pseudoword reading was intact. On the word pair list, which mostly includes regular words, he did not make significantly more surface errors than the controls.

Table 3. Assessment of dyslexic participants using standardized French screeners: focusing on reading fluency and oral phoneme awareness. It's notable that all participants achieved scores within the expected range for their respective grade levels. Percentile ranges rather than exact percentiles for each subject are provided for the Alouette screener. The range provided in the column for each student describes their placement range according to the Alouette. For pseudoword repetition, phoneme-fusion and suppression 'M' represents the number of standardized correct responses, while 'SD' indicates the number of errors corresponding to one standard deviation from this mean. For each participant we provide their number of correct responses. 'I' is the total number of items in the test.

Subj: sex, grade	Alouette percentile range	Pseudoword repetition + M = 19, SD = 1	Phoneme fusion* M = 7.5, SD = 2.4	Phoneme suppression* M = 8.3, SD = 2.0
		I = 20	I =10	I = 10
LP: m, 6	25–50%	20	9	9
TR: m, 7	25–50%	20	7	8
LD: f, 7	25–75%	20	10	10
JB: m, 6	50–50%	19	9	8
PO: m, 7	25–50%	20	7	8
HW: m, 7	25–50%	20	8	8
JC: m, 6	25–50%	20	8	8

+Standardized scores are not provided after 5th grade, when normal readers are at ceiling. This was clearly also the case for our participants.
* Standardized scores are provided for the 7th grade (the screener has not been normed for the 6th grade).

5.2. Could the participants' dyslexia be detected by traditional French screeners?

An important result is that none of the seven participants described above whose dyslexia was identified using the MALABI would be considered at risk for dyslexia by the Alouette reading test (see Table 3, a deficit is considered at < -2SD from the mean). All their scores in the Alouette, except for JB, were between the 25th and 50th percentile on the Alouette, and JB's performance was even above the mean. This result reveals very clearly the importance of the use of stimuli that are sensitive to the various types of dyslexia: individuals who have a selective letter-position deficit will only be identified by a test that includes migratable words; individuals with a selective deficit in letter-to-word binding (attentional dyslexia) will only be identified with tests that include words in the context of other words that create migratable pairs; individuals with surface dyslexia will only be identified with lists of unpredictable, potentiophonic, and irregular words, and so on. Given that the Alouette does not contain the relevant stimuli to identify migrations within or between words, these students were identified with dyslexia using the MALABI but not with the Alouette.

5.3. Dyslexia, but no phonological impairment

All seven students with dyslexia who were described above performed within the normal range on the tasks testing oral language and phonological awareness, as summarized in Table 3.

6. Experimental investigation of attentional and letter-position dyslexia profiles

6.1. Method

6.1.1. Participants

Having found seven tentative cases of specific dyslexia types using the Malabi screener, we recontacted these students to evaluate if our inferences could be replicated, and to shed light on the factors that modulate their reading errors. Four of these students were available for further testing: three of the students who made between-word migrations on the initial Malabi screener and were therefore identified as having attentional dyslexia (LP, TR, LD) and one of the students with within-word transposition errors (JB), who was

Table 4. Types of word-pairs in the list targeting attentional dyslexia– letter migrations between words. For all pairs, the migration could move from the left to right word or the right to left word. Consonants were always migratable for consonants (650 possible lexical migrations) and vowels for vowels (502 possible lexical migrations). In the error analysis, errors were only counted as between-word migrations only when a letter migrated from one word to the other if it maintained its position. For first and last letters this was the exact position, while middle letters could be anywhere in between. We counted each migration made, so that a double migration (bête fois read as "fête bois") was counted as two migrations, and a single-direction error (bête fois read as "fête fois") was counted as one.

Number of letters	Number of different letters between words	Position of migration	Number of pairs	Number of possible lexical migrations (1152)	Target pair	Possible migration
Migratable word pairs (468)						
4	All	First	20	40	bête fois	fête bois
		Middle	20	40	sale fois	sole fais
		Last	20	40	aime volé	aimé vole
	One	First	20	40	loin soin	soin loin
		Middle	20	40	fuit fait	fait fuit
		Last	20	40	fous four	four fous
	Two	first_last	12	48	fini mine	mini fine, fine mini
		first_middle	12	48	poux deux	doux peux, peux doux
		middle_last	12	48	dura dire	dira dure, dure dira
5	All	First	20	40	flans paire	plans faire
		Middle	20	40	repue laver	revue laper
		Last	20	40	monté gagna	monta gagné
	One	First	20	40	banal canal	canal banal
		Middle	20	40	douce douze	douze douce
		Last	20	40	marié marie	marie marié
	Two	first_last	12	48	serai feras	ferai seras, seras ferai
		first_middle	12	48	belle salle	selle balle, balle selle
		middle_last	12	48	bougé boude	boudé bouge, bouge boudé
6	All	First	20	40	réparé soutes	séparé routes
		Middle	20	40	bottés lampes	bottes lampés
		Last	20	40	acheté pleura	acheta pleuré
	One	First	20	40	otages étages	éttages otages
		Middle	20	40	places plages	plages places
		Last	20	40	devine deviné	deviné devine
	Two, different letters and two opportunities for migration.	first_last	12	48	drainé graine	grainé draine, draine grainé
		first_middle	12	48	centre vendre	ventre cendre, cendre ventre
		middle_last	12	48	marges manger	manges marger, marger manges
Non-migratable word-pairs (60)						
4			20	0	joli gros	
5			20	0	balai taper	
6			20	0	reflet occupé	

therefore identified with letter-position dyslexia. They were tested 22 months after they had been tested with the Malabi. Six control students from Paris schools, matched to the earliest grade-year (8th grade) of our dyslexic participants, were also tested for comparison.

6.1.2. Stimuli for further testing of attentional dyslexia

Attentional dyslexia was further tested by a new list of 528 word-pairs. These included 468 migratable pairs in which a between-word letter migration would create another existing word, (1152 possible lexical migrations), and 60 pairs in which no between word position preserving letter migrations would create an existing word (see Table 4 for details). These words did not allow for transpositions within the word either. The two words in each pair had the same number of letters, between 4 and 6 letters. All pairs allowed for migration in either direction, and all of the different possible word pairs were presented, but never on the same page (e.g., lent vois; vois lent; vent lois; lois vent). The words ranged in frequency between 0 and 8,296 per million, M = 158 (frequencies taken from the Lexique French database, New et al., 2004). There was no difference in frequency between the words in the migratable and non-migratable categories, $p = .38$.

In the error analysis, errors were counted as between-word migrations only when a letter migrated from one word to the other if it maintained its position. For first and last letters this was the exact position, while middle letters could be anywhere in

Table 5. Types of words included in the 406 words list targeting letter-position dyslexia.

	Number of items	Example target -> *transposition error*
Transposable words (304)		
Middle transposition		
Adjacent consonant-consonant (CC) migration	26	congé -> *cogné*
Adjacent including a vowel (VV or CV) migration	110	loin -> *lion*
Non-adjacent consonant-consonant migration (C-C)	6	préside -> *prédise*
Non-adjacent including vowel migration (C-V, V-V)*	14	clouer -> *couler*
Exterior transposition		
Adjacent consonant-vowel (CV) migration	68	lier -> *lire*
Non-adjacent consonant-consonant migration (C-C)	66	coude -> *douce*
Non-adjacent including vowel migration (C-V, V-V)	14	pela -> *pale*
Non-transposable words	102	Maison

* Unlike non-adjacent pairs in the other categories, whereby the two letters could make a same position switch, these were all words that allowed for the rearranging of middle letters that were orthographically not adjacent to make a new word. This difference in the category was due to the absence of stimuli in French orthography characterizing an exact position transposition.

between. We counted each letter migration, so that a double migration (bête fois read as "fête bois") was counted as two migrations, and a single-direction error (bête fois read as "fête fois") was counted as one.

6.1.3. Stimuli for further testsing of letter-position dyslexia

Letter-position dyslexia was further tested using a single word reading-aloud test comprising 406 new words: 304 migratable words, i.e., words that had a possible letter transposition that would make another existing word and 102 nonmigratable words, which did not have such an anagram (see Table 5 for details). Each word and its anagram were present in the list. The words ranged in frequency between 0 and 14,662 per million, M = 151 (frequencies taken from the Lexique French database, New et al., 2004). For each word and its anagram, the frequency of the most frequent word was M = 68 per million (SD = 157) and M = 10 (SD = 26) for the least frequent. There was no difference in frequency between migratable and nonmigratable words, $p = .59$.

6.1.4. Statistical analysis

Within-participant comparisons between two conditions were conducted using chi-squared tests. Crawford and Howell's significance t-test was used to compare the performance of each participant with the control group (Crawford & Garthwaite, 2002; Crawford & Howell, 1998).

6.2. Results

6.2.1. Double dissociation between letter transpositions within words and letter migrations between words

We first sought to confirm the existence of a double dissociation, suggested by the initial Malabi screener, between attentional dyslexia (causing letter

Table 6. Percentage of errors made by dyslexic and control participants for two error types: migrations between words in the word-pairs tests, and within-word letter transpositions in the single-word test. Percentages were calculated by dividing the relevant number of errors by the total number of words on a test permitting the tested error type (migrations = 1152, transpositions = 304).

	LP, attentional dyslexia	TR, attentional dyslexia	LD, attentional dyslexia	JB, letter-position dyslexia	Controls N = 6 M(SD)
Between-words migration (N = 1152 items)	**5.7%** (6.9%)	**6.8%** (7.2%)	**4.4%** (4.5%)	1.2% (4,9)	0.9% (0.7)
Within-word transpositions (N = 304)	2.6% (5.3%)	0.7% (4.6%)	1.0% (3.9%)	**11.5%** (16.1%)	1.7% (1.6)
Between-word migrations vs. within-word transpositions (χ^2)	$\chi^2 = 4.78$, $p = .029$*	$\chi^2 = 17.31$, $p < .001$***	$\chi^2 = 7.97$, $p = .005$**	$\chi^2 = 78.43$, $p < .001$***	$\chi^2 = 1.61$, $p = .20$
Between-word migrations compared to controls~	t(5) = 6.73, $p < .001$***	t(5) = 8.18, $p < .001$***	t(5) = 4.93, $p = .002$***	t(5) = 0.48, $p = .33$	
Within-word transpositions compared to controls~	t(5) = 0.55, $p = .30$	t(5) = -0.61, $p = .28$	t(5) = -0.42, $p = .35$	t(5) = 5.76, $p = .001$**	

~For t-tests, we report the Crawford & Howell's and Crawford and Garthwaite's t-test for the comparison of an individual to a control group (Crawford & Garthwaite, 2007; Crawford & Howell, 1998).
* < 0.05, ** < 0.01, *** < 0.001.

migrations between words, as observed in participants LP, TR, and LD) and letter-position dyslexia (causing letter transpositions within words, as observed in participant JB). To test this, we had all four students read both the word-pair test with 468 migratable pairs and the single word test with 304 migratable words.

The performance of the four participants with attentional or letter-position dyslexia and of the controls is summarized in Table 6. The findings are clear-cut: a double dissociation was found between letter-position encoding within and between words. Each of the three participants with attentional dyslexia made significantly more between-words migrations than the control group whereas their rate of within-word transpositions did not differ from the controls' (Crawford & Garthwaite, 2005; Crawford & Howell, 1998). The participant with letter-position dyslexia exhibited the other direction of the dissociation, with significantly more within-words transpostions than the control group and a between-word migrations rate that did not differ from the controls'. A chi-square dissociation analysis indicated that each of these participants exhibited a classical dissociation.

Furthermore, the three participants with attentional dyslexia made significantly more between-words migrations than the participant with letter-position dyslexia; the participant with letter-position dyslexia made significantly more within-word transpostions than the participants with attentional dyslexia.

For the three participants with attentional dyslexia, migrations between words on the word-pair test far outnumbered any other type of errors. LP made 80 errors, 66 of them (83%) explainable as migrations between words. Similarly, 78 of TR's 84 errors were migrations between words (93%) and 51 of LD's 52 errors (98%) could be categoried as migrations between words. The opposite picture emerged for participant JB: he made a significantly greater number of within-word transpositions than of between-word migrations, with 35 transpositions (71%) out of 49 total errors. Together, these results confirm the inferences arising from the Malabi screener and indicate a double dissociation between attentional dyslexia and letter-position dyslexia, namely, between letter-position encoding between- and within-words.

7. Discussion

We developed a novel reading screener, the Malabi, designed to allow the identification of different types of reading errors in French. Using the Malabi, we were able to identify types of developmental dyslexia that have not been reported before in French. We documented 3 cases of attentional dyslexia and one case of letter-position dyslexia. The Malabi also identified 3 other potential cases: letter-position dyslexia (1 other student), phonological dyslexia (in grapheme-to-phoneme conversion, 1 student) and surface dyslexia (student). These students would not have been identified as having dyslexia using the currently available tests in French.

As a second step, we used further tests to examine the properties of two kinds of dyslexia: attentional dyslexia, a deficit in letter-to-word binding that manifests itself in between-word migrations; and letter-position dyslexia, a deficit in letter-position encoding within words, manifesting in within-word transpositions. We found a double dissociation between the two functions, with 3 students who had migrations between- but not within words, and 1 student who had transpositions within-words but not between words. This finding supports the existence of dissociable cognitive processes of letter-position encoding within and between words, in line with previous studies in attentional and letter-position dyslexias (Friedmann, Kerbel, et al., 2010a, who reported individuals who make migrations between words but no migrations within words ; Friedmann & Rahamim, 2007, who reported individuals who make migrations within words but no migrations between words). Other studies not purely interested in double dissociation have also reported differences in subjects within- and between word migrations. For instance, a study interested in the possible relations between various dyslexia types and attention deficits reported 32 participants with letter-position dyslexia in the absence of attentional dyslexia, and 5 participants with the opposite profile (Lukov et al., 2015). Another report, testing the effect of mindfulness training on reading errors in dyslexia, reported 6 participants with letter-position dyslexia in the absence of attentional dyslexia (Tarrasch et al., 2016). Such double dissociations indicate that although both the encoding of letter-position within words and the encoding of letter-position between words occur at the early stage of orthographic-visual analysis, they involve different processes that can be independently altered during development.

As further discussed below, letter-position errors within words could arise from a deficit in the spatial resolution of orthographic visual analysis of letters, e.g., visual letter detectors in or prior to infero-temporal cortex (Davis, 2010; Davis & Bowers, 2006; Rajalingham et al., 2020), whereas migration errors between words could arise from an improper orthographic attentional selection and/or amplification of one out of several words, all of which are processed in parallel at an early visual level (McConkie & Rayner, 1975; Rayner, 1975; Snell & Grainger, 2019).

In both types of dyslexia, the presence of a lexical bias (almost all errors make plausible words) suggests that dyslexias at the orthographic-visual stage may be partially compensated by using the orthographic input lexicon, which retrieves the most plausible existing words in the face of partial letter information. In the case of letter-position dyslexia, both lexicality and frequency influence reading, exactly as would be expected from a "Bayesian reader" that optimally combines incoming perceptual evidence with lexical priors (Norris, 2006) (sentence-level contextual priors may also influence reading, see Smith & Levy, 2013). This finding, as well as the double dissociation between migrations within and between words, exemplifies the fact that developmental deficits can selectively affect a particular stage of the orthographic identification process while leaving subsequent lexical stages intact. Another important aspect brought to light by the present study is the longitudinal stability of the selective dyslexia profiles. Over a year elapsed from the first time that the students were identified with the Malabi test to their retesting with longer tests, yet these selective cases continued to show identical, double dissociations of error types.

Many previous studies have found that dyslexic readers can be impaired only in specific types of stimuli (Sotiropoulos & Hanley, 2017), for instance in case of selective developmental deficits of surface dyslexia (Castles, 1996; Friedmann & Gvion, 2023; Friedmann & Lukov, 2008; Zoccolotti et al., 1999) or phonological dyslexia (Campbell & Butterworth, 1985). However, whereas studies of selective deficits of the lexical and sub-lexical routes have historically focused on central reading processes (the lexical and sublexical routes) as described by the Dual Route Model, the present research provides additional evidence supporting a locus of some deficits within the orthographic visual analyzer. This finding highlights the need to better characterize the key processes that govern orthographic analysis. In the case of attentional dyslexia, this means considering the orthographic-attentional window that selectively amplifies information from a target word and filters out the letter information arising from other words. In this respect, our results concur with considerable prior research suggesting the existence of a non-conscious processing of parafoveal words (McConkie & Rayner, 1975; Rayner, 1975; Snell & Grainger, 2019) and the importance of selective attention during reading (Facoetti et al., 2006, 2008; Franceschini et al., 2012; Peyrin et al., 2011; Vidyasagar & Pammer, 2010). In the case of between-word migration errors in attentional dyslexia, it may be that the orthographic-attentional window that attributes specific letters to the target word and inhibits letters from surrounding words is less powerful than in normal readers, thus causing letters to hold their within-word position but assigned to the incorrect word.

With regard to letter-position dyslexia, the results could arise from an abnormal uncertainty about letter-position, resulting in ambiguous coding of the incoming letter string, particularly for letters inside the word. Even in normal readers, priming experiments indicate that information about letter-position is fragile, such that visual word recognition can be primed by the prior presentation of the same word with transposed letters, particularly under conditions of impoverished inputs (e.g., with flashed or masked words), and more so for middle letters (Perea & Lupker, 2003). These results are compatible with spatial coding models of reading and especially models of the orthographic stage, that differentiate the encoding of letter identity and relative position, as supported by a cumulative benefit in masked primes that share a letter and position, share a letter in a position once removed, and share neither letter or position (Davis & Bowers, 2006). Recent evidence from both behavioral, brain-imaging, and computational modeling studies suggest that the information flow may proceed directly from letter-position coding to lexical access (Agrawal et al., 2019, 2020; Hannagan et al., 2021; Woolnough et al., 2020). Most interestingly, the dominant effect of reading acquisition seems to be to refine the positional accuracy with which nearby letters are encoded (Agrawal et al., 2019; Kohnen & Castles, 2013). Letter-position dyslexia would occur at precisely that stage where each letter must be bound to a specific ordinal position, in order to avoid confusing anagrams.

The Dual Route Model was originally designed as a model of expert reading, and nicely accounts for acquired dyslexias. The present research lends behavioral support for its usefulness in also understanding at least some selective cases of developmental dyslexia (Perry et al., 2019). However, developmental reading deficits may entail an additional complexity beyond acquired ones, since an early deficit in one of the processes may hinder acquisition of the others. In the future, therefore, proper modeling of the present cases may require an explicit simulation of the learning process (Perry et al., 2019), possibly using recent detailed convolutional models of invariant word recognition (Hannagan et al., 2021).

Dyslexia (in the singular) has often been argued as stemming from a systematic phonological deficit in language processing, as supported by reports of poor phoneme processing in the majority of dyslexic cases (Landerl et al., 2013; Ramus, 2003; Saksida et al., 2016; Sprenger-Charolles et al., 2000; Ziegler et al., 2008). This argument is often supported by the importance of oral phoneme manipulation as a predictor of early literacy skills (Melby-Lervåg et al., 2012; Piquard-Kipffer & Sprenger-Charolles, 2013; Torgesen et al., 1997). While a precise representation of phonemes is clearly necessary to reading, the argument that poor phoneme processing is the exclusive core deficit of dyslexia has been contested (Castles, 1996; Castles & Coltheart, 2004; Castles & Friedmann, 2014; Friedmann & Rahamim, 2007; Güven & Friedmann, 2019, 2021, 2022; Khentov-Kraus & Friedmann, 2018). Causes and consequences are hard to disentangle since phonological awareness appears to be poor in illiterate adults (Schaadt et al., 2013) and gets refined during the acquisition of literacy (Dehaene et al., 2010, 2015a; Froyen et al., 2008; Monzalvo & Dehaene-Lambertz, 2013; Morais et al., 1986). Interventions to improve phoneme awareness only improve reading acquisition when learning phonemes is combined with learning of their corresponding grapheme (National Reading Panel, 2000; Zarić et al., 2021). Dyslexic children may develop strategies to avoid reading, therefore leading to poorer phoneme processing skills compared to normal readers.

Another argument against the phonological core deficit is the evidence of recruitment biases. It is possible that, in dyslexia diagnosis, an over-reliance on tests that tap into phoneme awareness created a bias towards students with a phonemic deficit. In France, the tools used by speech therapists, teachers, and researchers to identify dyslexia predominantly use oral phoneme awareness or pseudoword repetition tasks. This may have caused practitioners to specifically diagnose dyslexia, and therefore to refer to researchers participants in dyslexia studies, only in the presence of a phonemic deficit, thereby increasing their representation in the literature. Other types of dyslexia may have been discarded as poor readers. In this work, we assessed all seven cases with selective dyslexias (letter-position dyslexia, attentional dyslexia, grapheme-phoneme conversion, surface dyslexia) on tasks commonly used to test phonemic deficits, and found that all showed normal ability. All performed within the normal range on the Alouette test, pseudoword repetition, phoneme fusion, and phoneme suppression. Their dyslexias could not, therefore, be explained by an underlying phoneme processing deficit. Unfortunately, we do not know in these cases if it is because these children all received intensive language and reading support from their specialized school, or if they never had a phoneme deficit in the first place. At the very least, however, these cases indicate that phonological abilities can be normal in students with clear and reproducible dyslexia.

7.1. Limitations

Converging research points to the importance of early and individualized interventions for at-risk students in order to improve the effectiveness of remediation (Morris et al., 2010; Ozernov-Palchik et al., 2017; Shaywitz et al., 2008; Torgesen, 2002). The Malabi test, however, requires overt reading and can therefore only be used once a certain reading fluency has been attained. Future research should attempt to expand the screening to students in lower grades. A second limitation of the current work is that, while we report single-case studies of selective dyslexias, we cannot determine their frequency. Future research should seek to evaluate the prevalence of different types of selective deficits.

A third major limitation to the Malabi is its usability. Currently, testers must be trained to transcribe the errors in phonetic notation, and to attribute them to an appropriate level of the reading process. For example, if the reader read the word *signe* \siɲ\ as *singe* \sɛ̃ʒ\, the tester must recognize that this phonological output could have arisen from a single letter transposition. Such detailed error coding is far more time-consuming than classical recordings of reading speed and accuracy, particularly for severe dyslexics who make many errors. We are working towards automating the error-coding process by compiling a large database of the most frequent errors and their codes. Manual phonetic transcription could also be avoided once accurate speech recognition becomes available for children. Besides this initial hurdle, for a practitioner to use the Malabi, they must also be sensitive to when an error may meet multiple criteria and which follow-up tests should be used to disambiguate the readers dyslexia. This is a complicated process requiring experience and knowledge of the different dyslexias types and their features. In other words, the Malabi requires far greater knowledge of the research in dyslexia than is required by the more frequently used tests that categorize readers by speed and accuracy.

7.2. Future directions

In considering the importance of early diagnosis and test usability, we argue for a multi-step process to mitigate the effects of dyslexia. This process would begin with pre-reading language and visual testing of all children on known predictors of reading, using tests that can be easily administered by teachers and may spot students that need individual attention early in reading instruction (Ozernov-Palchik et al., 2017). To reduce confounding dyslexia with a possible poor learning environment, learning to read in school should then follow an evidence-based explicit phonics curriculum known to best help all students, including those who are most at risk for dyslexia (Castles et al., 2018; Conseil scientifique de l'éducation nationale, 2019; Ehri et al., 2001; National Reading Panel, 2000). Finally, children who still show poor reading outcomes despite optimal circumstances could be assessed with a screener such as the Malabi, administered by a trained tester. Based on its outcomes, a detailed model of the child's reading deficit, be it selective or mixed, would then guide individualized remediation (Perry et al., 2019). The Malabi provides a more detailed account of the possible sources of errors than other screeners, and its potential to pinpoint the sources of their dyslexia therefore seems better than a general diagnosis of slow or inaccurate reading.

The possibility that multiple specific deficits underlie the umbrella term "dyslexia" also has consequences for brain imaging and genetics. The existence of distinct types of dyslexia, with doubly-dissociated performance on specific tests, is not surprising, neither from the perspective of classical adult cognitive neuropsychology where such dissociations have been attested (Beauvois & Derouesne, 1979; Campbell & Butterworth, 1985), nor from the perspective of multiple-route models of reading (Coltheart, 2005; Coltheart et al., 2001; Friedmann & Coltheart, 2018), which clearly point to the possibility that many different impairments may result in a reading deficit. However, it has many consequences for large-scale studies of the genetic or neurological basis of those deficits, which often treat "dyslexia" as a single entity. By doing so, they run the risk of identifying very broad genetic risk factors, for instance related to intelligence or education (Gialluisi et al., 2020) or, in the case of brain imaging, the generic consequences of non-proficient reading rather than the specific causes of the reading deficit (Dehaene et al., 2015a; Feng et al., 2020; Maisog et al., 2008; Martin et al., 2015; Rueckl et al., 2015). The present results suggest that a careful analysis of behavior, based on the existence of distinct types of errors, should precede, guide, and facilitate the mechanistic understanding of the various causes of reading impairments, as well as improve the efficiency of their rehabilitation. One place to start would be testing for the similarity of selective deficits in cases where dyslexia runs in families, as there is strong evidence for familial transmission (Cardon et al., 1994; Defries et al., 1978; Gialluisi et al., 2020; Pennington et al., 1991; Plomin et al., 1997).

Finally, the ultimate goal of improved assessment is to provide targeted remediation (Fletcher &

Grigorenko, 2017). Specific interventions for selective dyslexia should reduce the impact of dyslexia in daily life. In the majority of cases, dyslexia does not make reading impossible, only difficult. Previous research, although scant, has shown that remedial training, or tactics that alleviate the deficit, may help the learner re-engage in reading. For example, training of grapheme-to-phoneme conversion rules has been shown to improve cases of phonological dyslexia that stem from deficits in the grapheme-to-phoneme conversion route (Brunsdon et al., 2002; Kendall et al., 1998; Kiran, 2005). For errors of letter migration between words, the use of a cut-out window slid from word to word while reading was shown to reduce migrations from neighboring words, thus improving fluency (Friedmann et al., 2010; Rayner et al., 1989; Shvimer et al., 2009). It has also been suggested that crowding of nearby letters is a frequent source of errors in beginner readers and struggling readers (Martelli et al., 2009; Pelli et al., 2007), who may benefit from the s p a c i n g of letters (Zorzi et al., 2012). This simple adjustment of text spacing also seems to be a factor in alleviating letter transpositions for individuals with letter-position dyslexia (Friedmann & Rahamim, 2014).

7.3. Conclusion

By documenting a double dissociation between attentional and letter-position dyslexias on the Malabi screener and on follow-up tests, the present study supports the existence of selective deficits stemming from distinct steps of the orthographic visual analysis stage of reading. Importantly, this work in French adds to the growing body of languages in which there is evidence for specific dyslexia types resulting from deficits in the orthographic analysis stage (see, for instance, in Hebrew: Friedmann, Dotan, et al., 2010; Friedmann & Gvion, 2001; Friedmann & Rahamim, 2007; Arabic: Friedmann & Haddad-Hanna, 2014; English: Brunsdon et al., 2006; Ellis et al., 1987; Kohnen et al., 2012; Turkish: Güven & Friedmann, 2019, 2021, 2022; Italian: Lavelli et al., 2019; Traficante et al., 2021).

This work also highlights the importance of developing dyslexia screeners that include specific stimuli to detect selective deficits, according to the types of words and pseudowords most sensitive to each type of deficit, and to analyze specific types of errors, which are characteristic of different types of dyslexia, as opposed to just screening for the number of correct responses and reading speed, as is generally done in most dyslexia screeners. This approach may identify individuals with dyslexia who would otherwise be missed– none of the participants in our sample of highly trained dyslexic students were considered dyslexic on the traditional French test for dyslexia. Understanding dyslexia on the basis of error types to selected words will in turn help researchers and practicians to provide improved remediation tactics, tailored to each child's specific deficit.

Notes

1. Note that this particular type of error is linked to the deletion or addition of two separate letters that have two distinct grapheme-phoneme correspondences, as exemplified earlier. This error type should not be confused with geminate errors, where the reader incorrectly interprets a single grapheme-phoneme correspondence. For instance, mistakenly reading 'dessert' as 'desert'. Geminate errors may stem from a deficiency in the conversion of a geminate according to a multi-letter grapheme-phoneme correspondence rule, or from deficiency in the lexical route, when this is needed for the correct rendering of a geminate in a certain word.
2. In previously reported cases of selective deficits in letter position dyslexia and attentional dyslexia, readers did not make significant errors that could not be attributed to migrations. This distinction sets these selective categories apart from Visual-Orthographic Analysis, which encompasses a wide range of visual letter errors.
3. We have included the database of recorded errors for norms and dyslexics combined here, https://osf.io/3pgzb/.
4. To the degree that it was possible, we revisited these students with a second battery of tests to examine the possibilty that they had undiagnosed dyslexia. Several of these students were identified as having selective deficits.

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Appendix

Table A1. This table provides descriptions of various types of dyslexia screened by the Malabi. The 'number of stimuli' denotes the deliberately included test items designed to identify specific dyslexic characteristics. In these instances, the item's misreading, based on the 'trap' we had set, would result in a real word. The intention behind this approach is to create situations where readers with this type of dyslexia are less likely to auto-correct errors due to their unfamiliarity with the word. Items in italics represent sensitive stimuli within the French Malabi screener, strategically chosen to detect specific dyslexia categories. Words enclosed in quotes illustrate the potential reading responses that signify errors related to the respective dyslexic category. In certain instances, our coding scheme may assign an error to multiple dyslexia types. To assess a selective deficit, we need to review which error type occurred more frequently at a level significantly higher than that of the control group.

Dyslexia type	Typical errors	Malabi stimuli sensitive to that dyslexia type	Sensitive stimuli example -> possible error
Attentional	Migration of letters between neighboring words. The letter retains its within-word position. Omission of a letter that appears in the same position in two neighboring words	Word pairs in which a migration of a letter between neighboring words (horizontal or vertical distance < 2 items) that retains its within-word position makes a new word. **44** horizontal migratable word-pairs	*balle selle* -> "salle belle"
Letter-position	Letter transpositions within words and pseudowords. Omission of an instance of a doubled letter or doubling of a letter	Items in which a within-word transposition can form a new word. **44** migratable words **22** migratable pseudowords	*magner* -> "manger" *fotre* -> "forte"
Neglect	Omission, substitution, and addition of letters consistently on one side of the word/ nonword	Items in which an omission or substitution of a letter on the neglected side creates an existing word. **80** left-neglect words **60** right-neglect words **13** left-neglect pseudowords	*ruse* -> "use" or "muse" *cela* -> "la" *truche* -> "ruche" or "cruche"
Letter identity	Omission/substitution of letters (which cannot be explained by letter position dyslexia or attentional dyslexia, and are not consistent to one side of the word)	Examined through all words and pseudowords in the test. Specific testing of letter identity is required as a follow-up test.	*prie* -> "plié"
Orthographic-visual analyzer	Omissions, substitutions, and additions of letters, letter-position, and migrations between words	Examined through all words in the test. Omission, substitution, addition of consonants, that cannot be explained by attentional or letter position dyslexias.	*bras* -> "bas" *vole* -> "vote"
Grapheme-phoneme conversion	Difficulty reading new words and pseudowords. Reading through the mental lexicons is intact	Easily pronounceable pseudowords **40** pseudowords	*flache* -> "flaque"
Phonological Output Buffer/ orthographic input buffer	Difficulty with long or morphologically complex words and pseudowords, function words, number words	Morphologically complex, function, number words. **38** Long words and pseudowords, **40** morphologically complex **8** number words **13** function words 40 pseudowords (incl. 5 morphologically complex)	*marcherions* -> "marchons" *trois* -> "treize" *mais* -> "car"
Vowel	Vowel omissions, migrations, substitutions, and additions in pseudowords (and words, when read via the sublexical route, such as in cases with surface dyslexia). More vowel errors than the control group, not more consonant errors.	Items in which a vowel error forms another word. **73** words allowing for omission, substitution, or addition of a vowel letter **20** pseudowords	*lueur* -> "leur" *troche* -> "triche" *noveau* -> "nouveau"
Surface	Regularization of letters, digraph, and diphthongs in irregular and unpredictable words.	Irregular, but frequent, words. **97** single words (59 of which are potentiophones)	*fille /fij/* -> "fil /fil/" *parfum /paʁfœ̃/* -> "parfume /paʁfym/"
Deep	Semantic errors and associations (reading another word of a related meaning). Severe difficulty with nonwords, abstract words, function words and number words.	**40** morphologically complex words **40** pseudowords **25** abstract words	*boulangerie* -> "croissant" *trois* -> "treize"